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Initial Surface Absorption of Cement Combination Concretes Containing Portland Cement, Fly Ash, Silica Fume and Metakaolin

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Abstract

In order to support the use of cement combination concrete in construction, this paper investigated the initial surface absorption of cement combination concrete using Portland cement and some binary and ternary cement concretes containing fly ash, silica fume and metakaolin as partial replacements for Portland cement at equal water/cement ratios and strengths. At equal water/cement ratio, the cement combination concretes have higher initial surface absorption values than Portland cement concrete at 28 days and the disparity reduced due to improved pozzolanic reactivity of the supplementary cements with increasing curing age. However, silica fume and metakaolin as binary and ternary cement components performed better than fly ash due to their higher fineness, improved particle packing and higher pozzolanic reactivity. At equal strengths, fly ash binary cement concretes have the lowest ISAT 10 values and they reduced with increasing content of fly ash. At total replacement levels more than 20%, all the ternary cement concretes have lower ISAT 10 values than Portland cement concrete and the values reduced with increasing total replacement level due to the beneficial effect of fly ash. Hence, high volume of fly ash would be required to improve the resistance of concrete against permeation.

Keywords: *Blended cement, cement combination concrete, initial surface absorption, permeation resistance, supplementary cement.*

1.0 Introduction

Cement combination concrete is used in order to reduce the cost and environmental impact of Portland cement concrete [1]. However, while BS EN 197- 1 [2] permits the use of silica fume, metakaolin (a natural calcined pozzolana), fly ash and Ground Granulated Blast-furnace Slag (GGBS) of up to 10%, 35%, 55% and 95% respectively, data from the European Ready Mixed Concrete Organisation [3] showed that the total supplementary cement (fly ash and GGBS only) content in ready-mixed concrete is less than 20% of the total cement consumption. Hence, to support the use of cement combination concrete, this paper investigated the initial surface absorption after 10 minutes (ISAT 10) of cement combinations concretes containing Portland cement, fly ash, silica fume and metakaolin. This is because ISAT 10 values could be used to determine the resistance of the surface zone of concrete (which protects reinforcing steel against corrosion) against water penetration from driving rain [4]. Hence, the resistance of the surface zone of concrete to permeation is an important indication of the quality of concrete.

Silica fume and metakaolin, due to their high fineness, would result in close packing, generate more nucleation sites to accelerate cement hydration and produce hydrated materials capable of improving the strength and reducing the pore size, porosity and permeability of concrete [5-13]. However, their high fineness would result in workability problems [14-18]. Fly ash, due to its availability, low cost and quality control, is used as a primary pozzolana in blended cement concrete [19]. However, while it is characterised by low water demand and improved workability [20, 21] and relatively poor characteristics at early ages [9], its pozzolanic reactivity improved with curing age [22] to improve the resistance of its concrete to permeation [23, 24]. Hence, ternary combinations of Portland cement, fly ash and silica fume or metakaolin would reduce the water demand and superplasticiser dosage associated with silica fume and metakaolin and compensate for the slow rates of reactions of fly ash at early ages to enhance both early and later age performance of concrete [20, 22, 25-27].

Furthermore, while concrete in practice is specified on the basis of strength, most researches in literature were conducted at different water/cement ratios with Portland cement, fly ash and either silica fume or metakaolin thus preventing cross deduction between results and equal basis for the comparison of the performance of silica fume and metakaolin. Hence, this paper investigated the ISAT 10 of Portland cement concrete, binary cement concretes containing fly ash, silica fume and metakaolin as partial replacements for Portland cement and ternary cement concretes containing Portland cement, fly ash and silica fume or metakaolin at equal water/cement ratios and strengths.

2.0 Experimental Materials

The cements used were Portland cement (CEM I, 42.5 type) conforming to BS EN 197- 1 [2], siliceous or Class F fly ash (FA) conforming to BS EN 450- 1 [28] and silica fume (SF) in a slurry form (50:50 solid/water ratio by weight) conforming to BS EN 13263- 1 [29] and metakaolin (MK) conforming to BS EN 197- 1 [2]. The properties of the cements are presented in Table 1. The aggregates consisted of 0/4mm fine aggregates and 4/10mm and 10/20mm coarse aggregates. The coarse aggregates were uncrushed and they come in varied shapes. The 4/10mm aggregates have rough texture and the 10/20mm aggregates were smooth. The physical properties of the aggregates are presented in Table 2.

Table 1: Properties of cements

PROPERTY	CEMENTS			
	PC	FA	SF	MK
Blaine fineness, m^2/kg	395	388	*	2588
Loss on ignition, % [a)]	1.9	6.1 [b)]	2.7	0.9
Particle density, g/cm^3	3.17	2.26	2.17	2.51
% retained by 45µm sieve [b)]	-	11.0	-	-
Particle size distribution, cumulative % passing by mass [c)]				
125 µm	100	100	100	100
100 µm	98.2	99.2	100	100
75 µm	93.2	96.5	100	99.8
45 µm	81.8	87.0	100	99.4
25 µm	57.1	66.2	98.8	96.0
10 µm	30.1	40.6	93.8	76.2
5 µm	13.5	24.1	87.5	50.7
2 µm	5.6	10.9	85.5	18.2
1 µm	2.9	4.8	78.7	4.7
0.7 µm	1.3	1.9	50.7	1.4
0.5 µm	0.2	0.3	10.5	0.1

* Fineness for SF = 15,000-30,000 m^2/kg [30]
a) In accordance with BS EN 196-2 [31]
b) In accordance with BS EN 450- 1 [28]
c) Obtained with the Laser Particle Sizer

Concrete was designed using the BRE Design Guide [32], saturated surface-dry (SSD) aggregates and a free water content of 165 kg/m^3 at the water/cement ratios of 0.35, 0.50 and 0.65. Potable water, conforming to BS EN 1008 [33], was used for mixing, curing and testing the concrete specimens. A superplasticiser based on carboxylic ether polymer, conforming to EN 934-2 [34], was applied during mixing to achieve a consistence level of S2 defined by a nominal slump of 50-90 mm in accordance with BS EN 206- 1 [35].

Table 2: Properties of fine and coarse aggregates

Property	Aggregates [1)]		
	Fine	Coarse	
	0/4 mm	4/10 mm	10/20 mm
Shape, visual	-	Varied	Varied
Surface texture, visual	-	Rough	Smooth
Particle density [2)]	2.6	2.6	2.6
Water absorption, % [3)]	1.0	1.7	1.2
% passing 600 μm sieve	55.0	-	-

1) Aggregates were obtained from Wormit Quarry.
2) In accordance with BS EN 1097- 6 [36]
3) In accordance with BS EN 1097- 6 [36], Laboratory-dry condition

3.0 Experimental Methods

Concrete was prepared to BS EN 12390- 2 [37] and the specimens were cast, cured under a layer of damp hessian covered with polythene for 20-24 hours, demoulded and cured in water tanks maintained at about 20^{o}C until the tests' dates. Tests were carried out on hardened concrete specimens to determine the cube compressive strength and initial surface absorption of the cement combinations at equal water/cement ratios. Cube compressive strength was obtained in accordance with BS EN 12390- 3 [38] using 100mm cubes at the curing age of 28 days at the water/cement ratios of 0.35, 0.50 and 0.65. Since absorption into concrete is a function of the drying temperature and immersion duration [39], initial surface absorption was determined with specimens oven-dried to constant mass at 105±5^{o}C to ensure a uniform basis for the comparison and repeatability of the results. This is because it is generally believed that at this temperature the pozzolanic reactions of the cement additions would be stopped, the plastic shrinkage cracking associated with reduced bleeding that normally characterise the use of fine materials would be avoided and the microstructure of the test specimens would not be adversely affected to prevent the repeatability of the results.

The initial surface absorption test (ISAT) is a low pressure assessment of the uniaxial water absorption per unit area of the surface zone (i.e. zone immediately behind the surface) of a concrete at a stated interval ranging from 10 minutes to 1 hour from the start of the test and at a constant applied head of 200mm of water which is slightly greater than that which would be caused by driving rain. The initial surface absorption after 10 minutes (ISAT 10) at the curing ages of 28, 90 and 180 days were obtained in accordance with BS 1881- 208 [4] using 150mm cubes subjected to water absorption at room temperature (20^{o}C). Each specimen was oven dried to constant mass at 105±5^{o}C, cooled to room temperature in a desiccator containing silica gel, installed as shown in Figure 1 and subjected to a pressure of 200mm head of water. For each curing age, the tap was turned off after 10 minutes to remove the applied water head and the average distance moved by water along the capillary tube in a minute, over three readings, was obtained and multiplied by the calibration factor of the tube obtained in accordance with BS 1881-208 [4] to obtain the ISAT 10 values for the specimens (Equation 1).

$$ISAT_t = N_t \times C_f \quad (1)$$

where $ISAT_t$ = Initial surface absorption t minutes after water first touched concrete surface.
N_t = Number of scale divisions moved, in a minute, t minutes after water first touched concrete surface.
C_f = Calibration factor of capillary tube determined in accordance with BS 1881- 208.

Figure 1: A typical ISAT set-up

4.0 Analysis and discussion of results

4.1 Initial surface absorption after 10 minutes of binary cement concretes at equal water/cement ratios

Figures 2 and 3 present the initial surface absorption after 10 minutes (ISAT 10 values) of Portland cement and fly ash, silica fume and metakaolin binary cement concretes at the water/cement ratios of 0.35, 0.50 and 0.65. As expected, the Figures show that ISAT 10 values increased with increasing water/cement ratio and reduced with increasing curing age. Compared with Portland cement, Figure 2 shows that ISAT 10 values of fly ash binary cement concretes increased with increasing content of fly ash. The increase must be due to the reduction in the Portland cement and $Ca(OH)_2$ contents (dilution effect) and the delayed pozzolanic reaction of fly ash [9, 40]. Figure 3 also shows that ISAT 10 values increased with increasing contents of silica fume and metakaolin up to 90 days. However, the disparity between the ISAT 10 values of Portland cement concrete and that of silica fume and metakaolin binary cement concretes reduced with increasing age such that at 180 days, the ISAT values were comparable with that of Portland cement concrete. Compared with fly ash, the higher resistance to permeation of silica fume and metakaolin must be due to their higher fineness resulting in improved packing and more nucleation sites for improved pozzolanic reaction to reduce pore size and porosity within the paste and at the interface transition zones between the paste and the aggregates [5, 12, 13] despite the dilution effect. Compared with metakaolin, the higher fineness of silica fume must have also resulted in the lower ISAT values of the silica fume binary cement concretes than the metakaolin binary cement concretes at equal replacement levels.

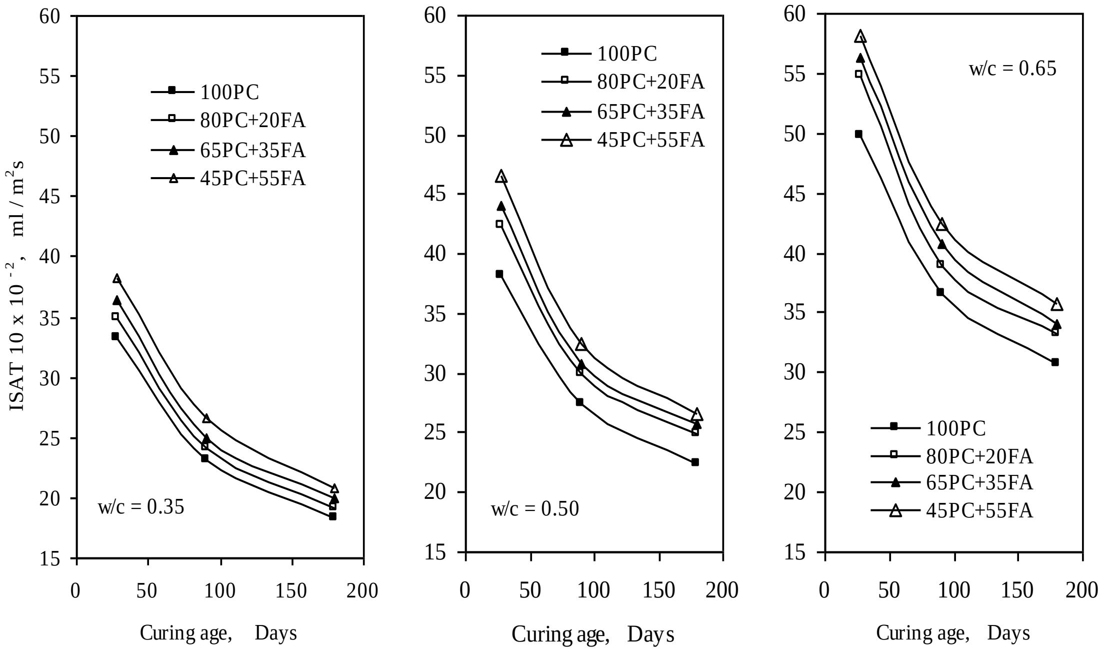

Figure 2: ISAT 10 of Portland cement and fly ash binary cement concretes at the water/cement ratios of 0.35, 0.50 and 0.65

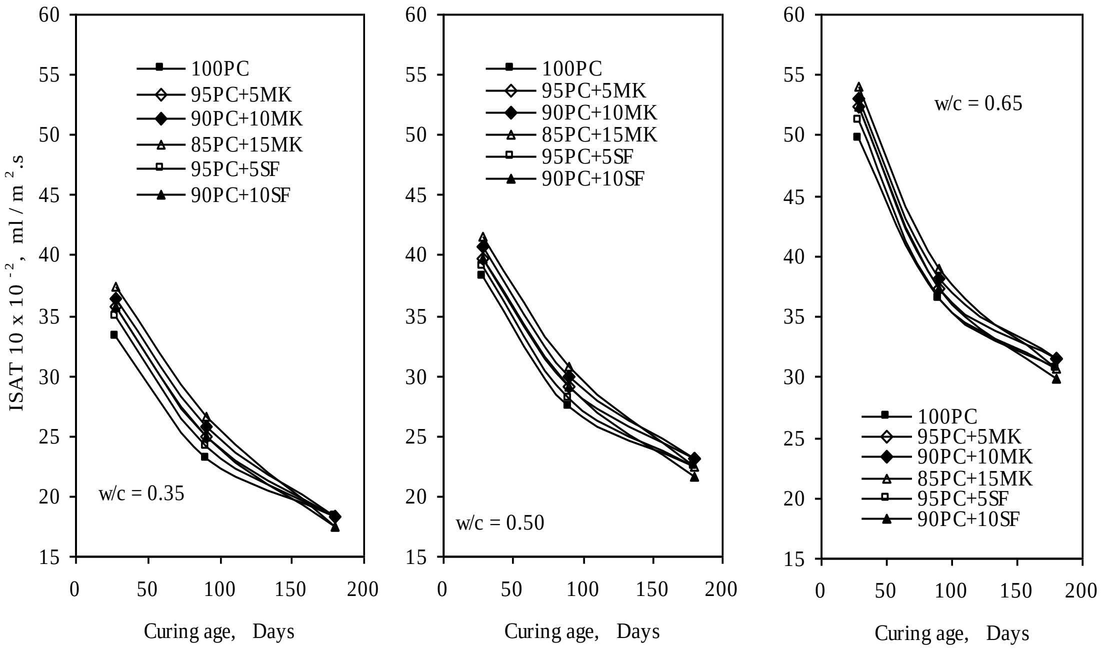

Figure 3: ISAT 10 of Portland cement and silica fume and metakaolin binary cement concretes at the water/cement ratios of 0.35, 0.50 and 0.65

4.2 Initial surface absorption after 10 minutes of ternary cement concretes at equal water/cement ratios

Figures 4-6 present ISAT 10 values of Portland cement, fly ash binary cement and silica fume and metakaolin ternary cement concretes at the total replacement levels of 20, 35 and 55% and water/cement ratios of 0.35, 0.50 and 0.65. Compared with the respective fly ash binary cement concretes, the addition of silica fume and metakaolin as ternary cement components (to partly replace the fly ash contents) reduced ISAT 10 values with increasing content at all the ages. Compared with Portland cement, the ternary cement concretes have higher ISAT 10 values at 28 days and the values reduced with increasing age such that at 180 days the values became comparable with that of Portland cement concrete. As stated above, the improved performance of the ternary cement concrete would be due to improved packing and high pozzolanic reactivity of the ternary cement components (i.e., silica fume and metakaolin) within the paste matrix and at the interface zone between the paste and the aggregates. Also, the higher fineness of silica fume must have also resulted in the lower ISAT 10 values of the silica fume ternary cement concretes than the metakaolin ternary cement concretes at equal replacement levels.

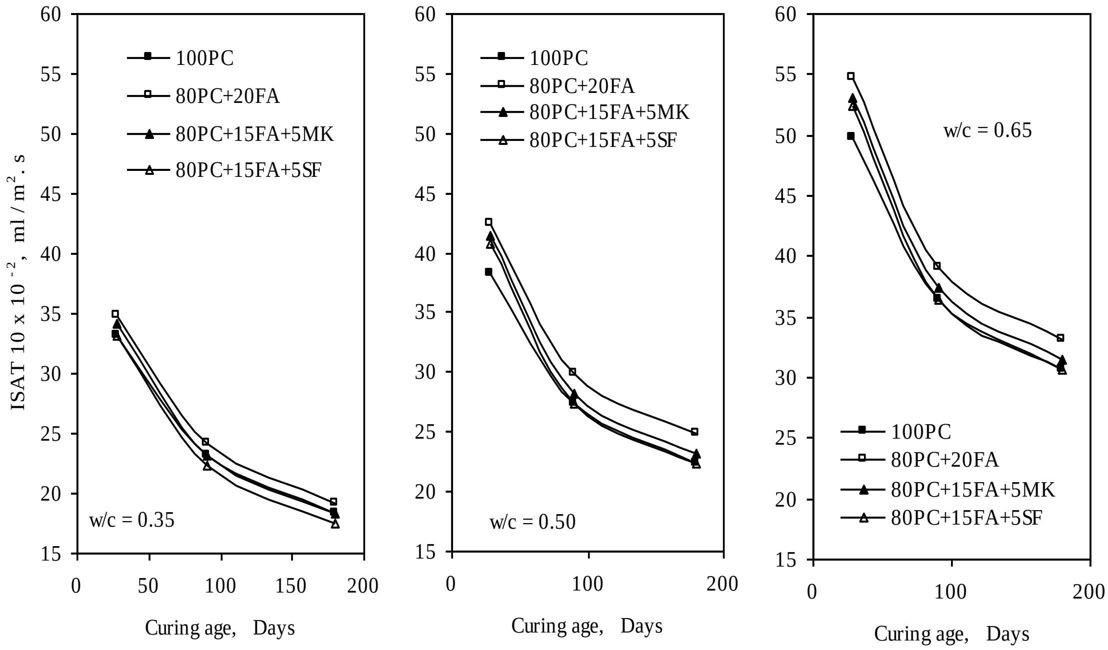

Figure 4: ISAT 10 of Portland cement, fly ash binary cement and silica fume and metakaolin ternary cement concretes at 20% total replacement level and water/cement ratios of 0.35, 0.50 and 0.65

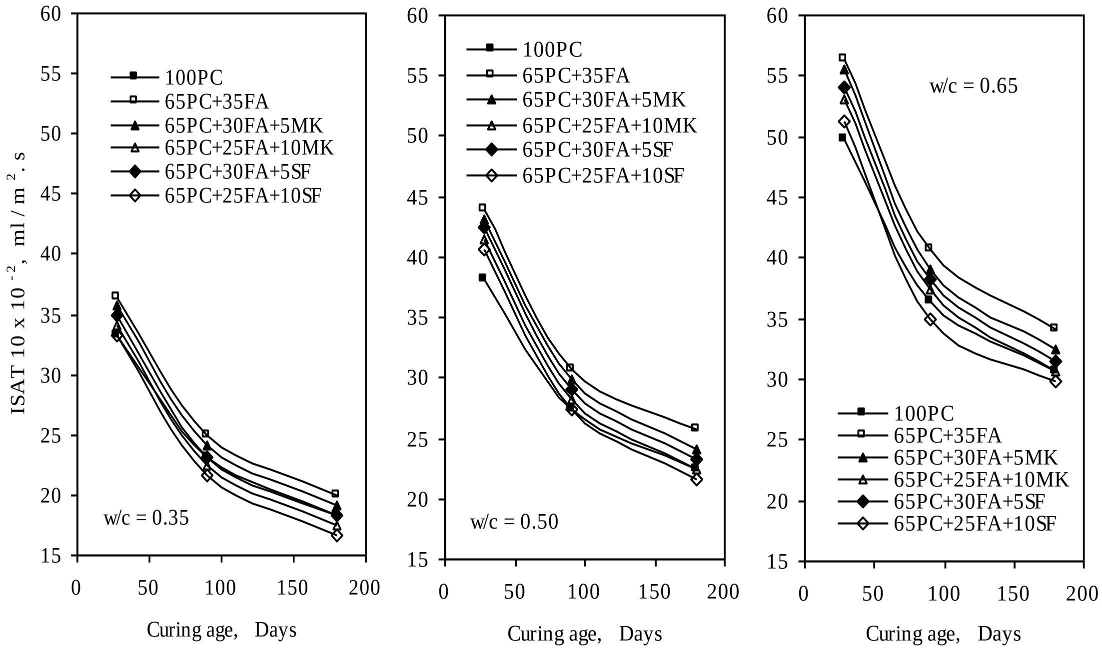

Figure 5: ISAT 10 of Portland cement, fly ash binary cement and silica fume and metakaolin ternary cement concretes at 35% total replacement level and water/cement ratios of 0.35, 0.50 and 0.65

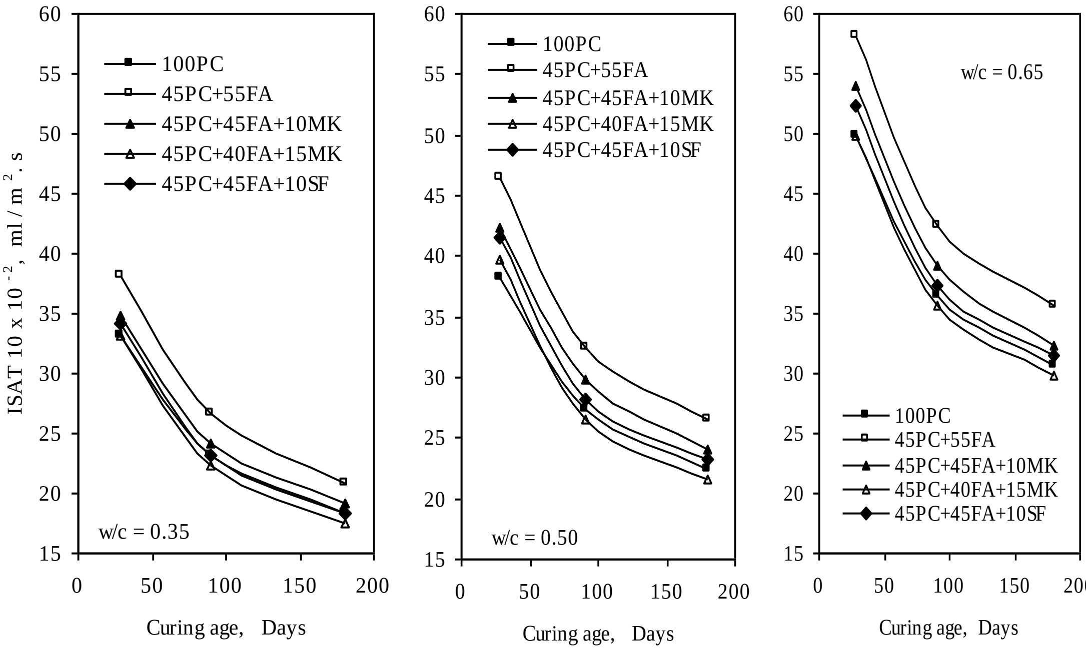

Figure 6: ISAT 10 of Portland cement, fly ash binary cement and silica fume and metakaolin ternary cement concretes at 55% total replacement level and water/cement ratios of 0.35, 0.50 and 0.65

4.2 Initial surface absorption after 10 minutes of cement combination concretes at equal strengths

Figures 7 and 8 show that cube compressive strengths of concretes at 28 days reduced with increasing water/cement ratio. Compared with Portland cement, while the addition of fly ash as a binary cement component reduced concrete strength with increasing content, the addition of silica fume and metakaolin resulted in comparable strengths with Portland cement concrete. Compared with the fly ash binary cement concretes, the addition of silica fume and metakaolin as ternary cement components resulted in ternary cement concretes with improved strength.

Since concrete is specified in practice on the basis of strength at 28 days, ISAT 10 values of the concretes were examined at equal 28-day strengths. The cube compressive strengths (Figures 7 and 8) and ISAT 10 values of the concretes at the curing age of 28 days (Figures 2-6) at the water/cement ratios of 0.35, 0.50 and 0.65 were interpolated to obtain the ISAT 10 values of concretes at the 28-day strengths of 35, 40, 45 and 50 N/mm^2 (Table 3). Apart from falling within the range of strengths that would commonly be used in practice, these strengths also satisfy most of the strength requirements in BS EN 206-1 [35] and BS 8500 [41, 42].

Table 3 shows that ISAT 10 values of concretes at equal strengths were achieved at different water/cement ratios and they reduced with increasing strength. Compared with Portland cement, all the fly ash binary cement concretes have lower ISAT 10 values at equal strengths and these values decreased with increasing content of fly ash. On the other hand, all the silica fume and metakaolin binary cement concretes have higher ISAT 10 values than Portland cement concrete and the values increased with increase in their contents. Compared with the respective fly ash binary cements, the ternary cement concretes have higher ISAT 10 values at equal strengths. Whereas, the ternary cement concretes have higher ISAT 10 values than Portland cement concrete at the total replacement levels of 20%, the values were lower than that of Portland cement concrete at the total replacement levels of 35% and they reduced with increasing total replacement level to 55%. This must be due to the beneficial effect of fly ash at equal strengths. Hence, high content of fly ash would play a major role in reducing the initial surface absorption of concrete specified on the basis of strength. These results indicate that, if appropriately proportioned, the use of cement combination would result in better resistance of concrete to permeation at equal strengths [43, 44]. Table 3 also shows that, at equal strengths, metakaolin binary and ternary cement concretes have lower ISAT 10 values than silica fume binary and ternary cement concretes at equal replacement levels.

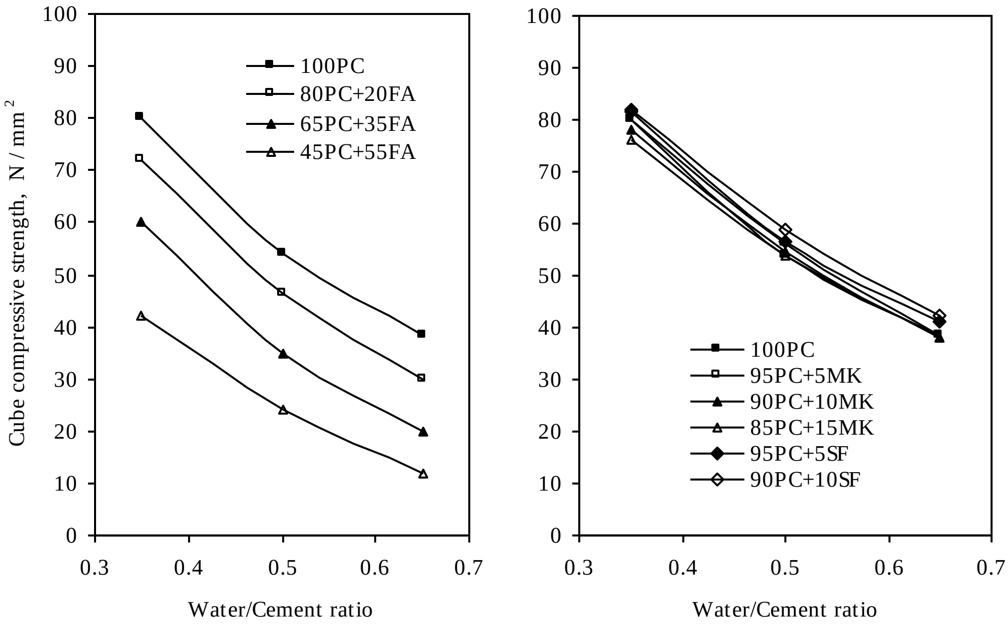

Figure 7: Cube compressive strength of Portland cement and fly ash, silica fume and metakaolin binary cement concretes at the water/cement ratios of 0.35, 0.50 and 0.65

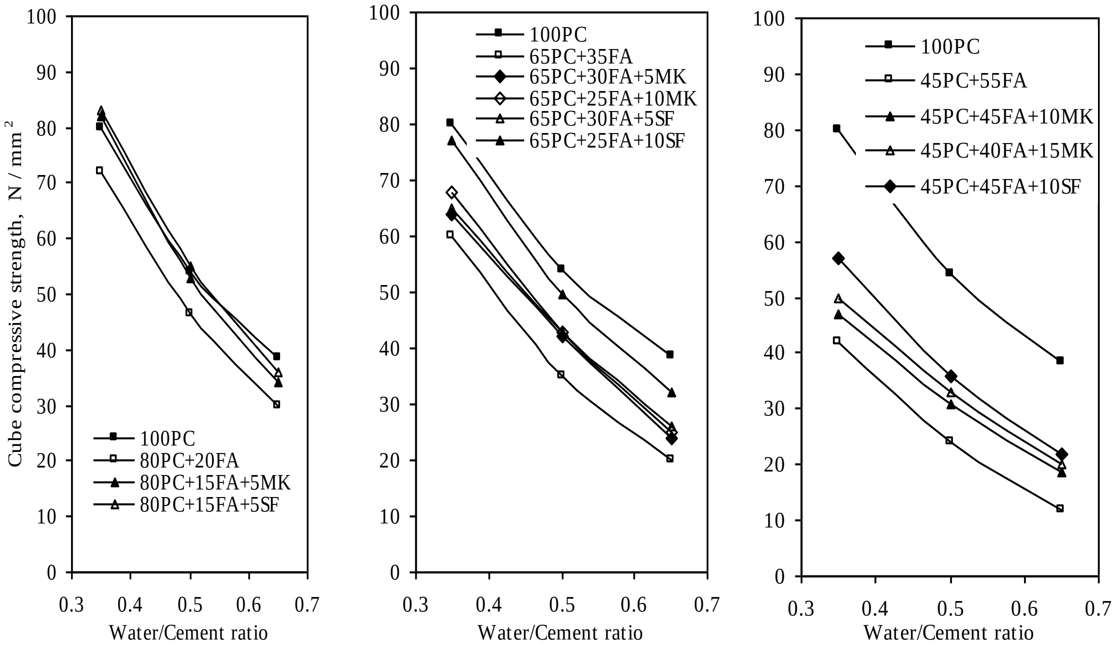

Figure 8: Cube compressive strength of Portland cement and ternary cement concretes at the water/cement ratios of 0.35, 0.50 and 0.65 and total replacement levels of 20, 35 and 55%

Table 3: ISAT 10 values of concretes at 28-day strengths of 35, 40, 45 and 50 N/mm^2

MIX COMBINATION	ISAT 10 x 10^{-2}, ml/m^2.s							
	35 N/mm^2		40 N/mm^2		45 N/mm^2		50 N/mm^2	
	w/c	ISAT 10	w/c	ISAT 10	w/c	ISAT 10	w/c	ISAT 10
100%PC	*	*	0.63	47.9	0.57	42.8	0.53	40.0
80%PC+20%FA	0.59	49.3	0.55	46.0	0.51	43.1	0.47	40.5
80%PC+15%FA+5%MK	0.63	51.3	0.59	48.0	0.55	44.9	0.51	42.2
80%PC+15%FA+5%SF	*	*	0.61	48.9	0.57	45.7	0.53	42.7
65%PC+35%FA	0.50	44.0	0.46	41.6	0.43	39.9	0.40	38.5
65%PC+30%FA+5%MK	0.55	46.8	0.51	43.9	0.47	41.4	0.44	39.7
65%PC+25%FA+10%MK	0.56	45.7	0.52	42.9	0.48	40.3	0.45	38.6
65%PC+30%FA+5%SF	0.56	46.6	0.52	43.8	0.48	41.2	0.44	39.0
65%PC+25%FA+10%SF	0.61	48.2	0.57	45.3	0.53	42.6	0.49	40.2
45%PC+55%FA	0.40	40.6	0.36	38.7	**	**	**	**
45%PC+45%FA+10%MK	0.47	40.6	0.42	37.9	0.37	35.7	**	**
45%PC+40%FA+15%MK	0.48	38.8	0.43	36.3	0.39	34.7	**	**
45%PC+45%FA+10%SF	0.50	41.5	0.46	39.2	0.42	37.2	0.39	35.8
95%PC+5%MK	*	*	0.63	50.3	0.58	45.5	0.54	42.4
95%PC+5%SF	*	*	0.62	50.0	0.57	45.5	0.53	42.6
95%PC+5%SF	*	*	0.62	50.9	0.57	46.3	0.53	43.4
95%PC+5%SF	*	*	*	*	0.60	46.3	0.55	42.2
90%PC+10%SF	*	*	*	*	0.62	49.2	0.57	44.7

5.0 Conclusion

This study has investigated the effect of fly ash, silica fume and metakaolin on the initial surface absorption of Portland cement concrete at equal water/cement ratios and strengths and the following conclusions have been drawn:

1. ISAT 10 value increased with increasing water/cement ratio and reduced with increasing curing age and compressive strength.
2. At equal water/cement ratio, the supplementary cements have higher initial surface absorption values than Portland cement concrete. However, while fly ash binary cement concretes have considerably higher initial surface absorption values than Portland cement concrete due to delayed pozzolanic reactivity; silica fume and metakaolin have values comparable with that of Portland cement due to their higher fineness and improved particle packing and pozzolanic reactivity. Hence, compared with fly ash binary cement concrete, silica fume and metakaolin ternary cement concretes have lower initial surface absorption values.
3. At equal strengths, while the addition of silica fume and metakaolin as binary cement components increased the initial surface absorption of concrete with increasing content, fly ash binary cement as a binary cement component reduced initial surface absorption with increasing content. Consequently, the initial surface absorption of the ternary cement concretes reduced with increasing total replacement level such that they became lower at total replacement levels more than 20%.

4. At equal replacement levels, while silica fume has higher resistance to initial surface absorption than metakaolin at equal water/cement ratios, metakaolin has higher resistance than silica fume at equal strengths.

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